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Dark Matter and Supersymmetry*

G. F. Giudice

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

Abstract

I review the possible candidates for cold dark matter suggested by supersymmetric theories and discuss the prospects for their experimental search.

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There is an emerging consensus[1)] that about 90% of the mass of the universe is made up of non–luminous matter, the nature of which is still unknown. Although this "dark matter" does not radiate any visible light, its existence can be revealed through its gravitational effects. Some of the best evidence for dark matter comes from the observation that the orbital velocities $v(r)$ of stars and gas clouds in spiral galaxies remain constant with the distance r from the center of the galaxy, even in regions where the luminous matter falls off exponentially. This fact, generally referred to as the flatness of rotation curves, implies that the matter contained within a distance r, $M(r) = v(r)^2 r/G$, increases linearly with r, or, equivalently, the mass density $\rho(r) \propto r^{-2}$. Therefore, the dark matter forms a halo which is distributed over a much larger volume than the visible galactic disk. There are several indications from the dynamics of galaxies that suggest that the dark matter halo is spheroidal and not flat, like the observed galactic disks. Thus, we are lead to assume that dark matter is dissipationless or else the halo would collapse. This means that, if some elementary particle is the constituent of dark matter, this particle should interact only weakly.[†]

Another hint for the presence of dark matter comes from the theoretical prejudice that Ω, the cosmological density in units of the critical density, should be equal to 1. From direct observations, we know that today Ω is approximately 1, within about an order of magnitude. In the standard Friedmann cosmology, $|\Omega - 1|$ increases with t. Therefore, if we do not accept an initial fine tuning, Ω must be exactly equal to 1. Moreover, inflationary models predict that $\Omega = 1$ holds exactly today. However, the successful predictions of nucleosynthesis about the abundance of light elements requires that the baryonic matter contribution to Ω should not exceed about 0.1. The problem is solved if dark matter accounts for the missing mass density.

[†]However, alternative models with strongly interacting particles have been suggested[2)].

If the dark matter is non–baryonic, what is its nature? One of the best motivated hypotheses for the nature of cold dark matter is suggested by supergravity theories[3]. If baryon and lepton number conservation is assumed, the low energy models derived from supergravity have an exact symmetry (generally called R–parity), which makes the lightest supersymmetric particle (LSP) stable. Some of the most plausible candidates for the LSP are found to be neutral, weakly interacting particles. Since the LSP is stable and annihilates in the primordial universe only through weak processes, it easily gives rise to a sizable contribution to the present Ω. In other words, the LSP is a promising candidate as constituent of the dark matter. In the following, I will describe three possible choices for the LSP: the neutralino, the sneutrino and the gravitino.

In most supergravity models, the LSP turns out to be a neutralino, a mass eigenstate mixture of the neutral spin 1/2 supersymmetric particles (photino, Z–ino, higgsinos,...). Since the neutralino is a Majorana particle, it cannot have a cosmic particle–antiparticle asymmetry, and its present relic density is completely determined in terms of its mass and its annihilation rate. The neutralinos annihilate in the early universe into fermion–antifermion pairs of ordinary matter through Z^0–exchange (via its higgsino component) or squark/slepton exchange (mainly via its gaugino component)[4–5]‡. Although these processes are of typical weak strength, the neutralino relic density can be considerably larger than the density of neutrinos with the same mass. This is true for several reasons. (i) The neutralino annihilation vanishes in s–wave, for massless final fermions[6]. This can be understood by noting that, in s–wave, the two identical neutralinos should be in a spin 0 state because of Fermi statistics. Since chirality is conserved in the interaction, the final massless fermions

‡I neglect for the moment neutralino annihilation into gauge or Higgs bosons.

have total spin 1 and thus the annihilation is necessarily p–wave suppressed. (ii) The neutralino interacts with the Z^0 only through the higgsino component and therefore it does not have a full weak coupling. (iii) The scalar partner exchange is suppressed when squarks and sleptons are heavy.

In the minimal supergravity models, the neutralino mass and its composition of current eigenstates are determined in terms of three free parameters: the two supersymmetric masses M and μ and the ratio v_2/v_1 of the two Higgs vacuum expectation values (see ref. 3 for reviews on supergravity models).

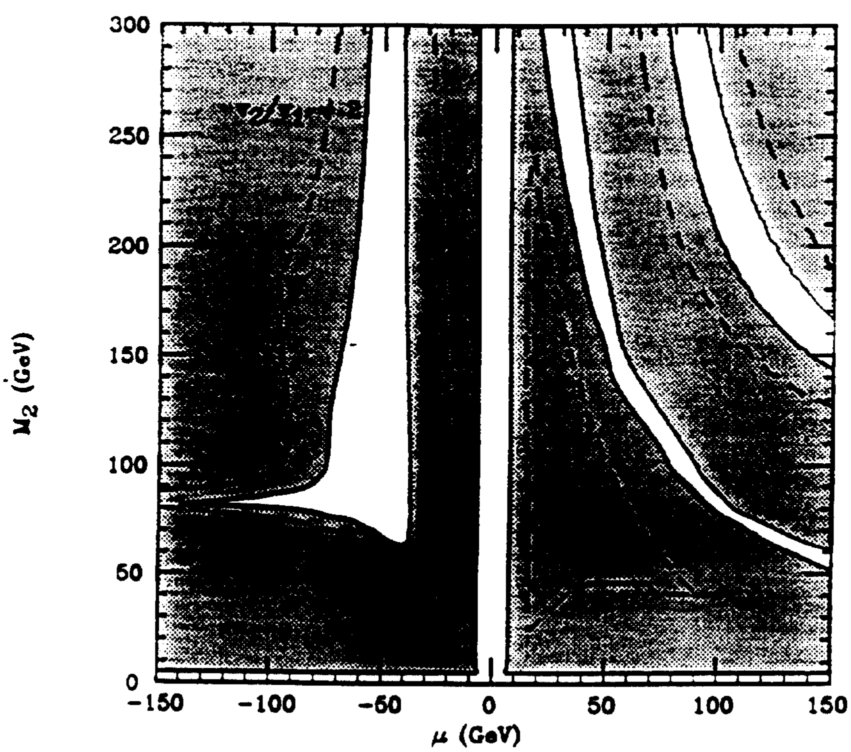

Fig. 1

Fig. 1 (from ref. 7), shows the region in $M - \mu$ space that can give rise to a neutralino density relevant for a dark matter solution, in the case $v_2/v_1 = 2$[§]. The

[§]Varying v_2/v_1 within a plausible range does not sensibly alter the result.

shaded region is the part of parameter space for which a neutralino contribution to Ωh^2 (h is the Hubble constant in units of 100 Km sec$^{-1}Mpc^{-1}$) in the range $0.025 - 1$ can be obtained with a choice of the squark/slepton masses compatible with present experimental limits. The dashed line delimits the region consistent with $\Omega = 1$, within the uncertainty on h ($0.4 < h < 1$). It is apparent that the neutralinos can be a good dark matter candidate in a vast range of parameters. The excluded regions correspond to two physical situations. (i) If the neutralino is lighter than few GeV, even with squark/slepton masses at their lower experimental limits, the annihilation rate is too small and the contribution to Ω too large. (ii) When the neutralino mass is close to $m_{Z^0}/2$, no matter what the squark/slepton mass is, the annihilation channel through Z^0 becomes very efficient and the contribution to Ω is very small. In all other cases, we can expect a significant cosmic neutralino density.

Although the neutralino is such an appealing candidate as a constituent of the galactic halo, the prospects for its experimental detection are less promising. The present laboratory limits on dark matter particles come from very low background germanium detectors, originally designed to search for double β decay[8)]. These experiments aim to discover the existence of cold dark matter through the detection of nuclear recoil due to the collision with an incident halo particle. If the dark matter particle has mass m and an average velocity of 300 km/sec, the maximum energy transfer in a collision with a germanium nucleus is about $(1 + \frac{76\,GeV}{m})^{-2}\cdot$ 150 keV. Since the present threshold is about 3 keV, the Ge detectors are able to constrain dark matter candidates with $m \gtrsim$ 12 GeV[8)]. This threshold is expected to be lowered soon. However, these limits do not apply to particles with only axial vector couplings (like Majorana neutrinos), since they have a spin dependent interaction with the nuclei, in the non–relativistic limit. Although neutralinos are Majorana particles, they can have spin–independent interactions with the nuclei. A first source of such interactions is a process mediated by squarks in the case in which the scalar partners of the left-handed ($\tilde{q}_L$) and right-handed ($\tilde{q}_R$) quarks are mixed[9]. Since most of the popular supergravity models predict that such mixing should be small, this effect is likely to be negligible. Squarks also mediate a spin–independent interaction when the neutralino contains both higgsino and gaugino components[5]. This stems from the fact that in the neutralino–q–$\tilde{q}_L$ interaction, the gaugino component of the neutralino couples only to left–handed quarks, while the higgsino component couples only to right–handed quarks and viceversa. The interference of the two couplings provides a scalar interaction of the neutralino to nuclei, which leads to a spin–independent interaction, in the non–relativistic limit. Since any realistic neutralino has both higgsino and gaugino components, this interaction is in general present. Unfortunately, in either of these scenarios, the neutralino scattering cross section off nuclei is suppressed by the fourth power of the squark mass and can be too small to be observable. However, a more promising contribution comes from Higgs boson exchange[7]. As shown in ref. 10, due to the effect of the trace anomaly, the Higgs coupling provides a coherent interaction with nuclei. If the Higgs boson is not too heavy, the *Ge* detector results already set limits on the neutralino, if it is the major component of the galactic halo. Fig. 2 (from ref. 7) shows the constraints on the supersymmetric mass parameters for a Higgs boson mass of 10 GeV (shaded region) and 20 GeV (dashed line), for $v_2/v_1 = 2$. Larger values of v_2/v_1 enhance the Higgs-neutralino coupling and give more stringent constraints.

A more indirect way of searching experimentally for cold dark matter has also been pursued[11]. The basic idea is that particles from the halo can lose their kinetic energy after a collision with a nucleus of the sun or the earth and then be trapped gravitationally. After equilibrium has been reached, the number of captured particles is equal to the number of particles that annihilate, if no evaporation process allows their escape. The annihilations of the dark matter particles can then yield a flux of energetic neutrinos. Underground detectors have already reported limits on such a flux of energetic neutrinos from the sun[12].

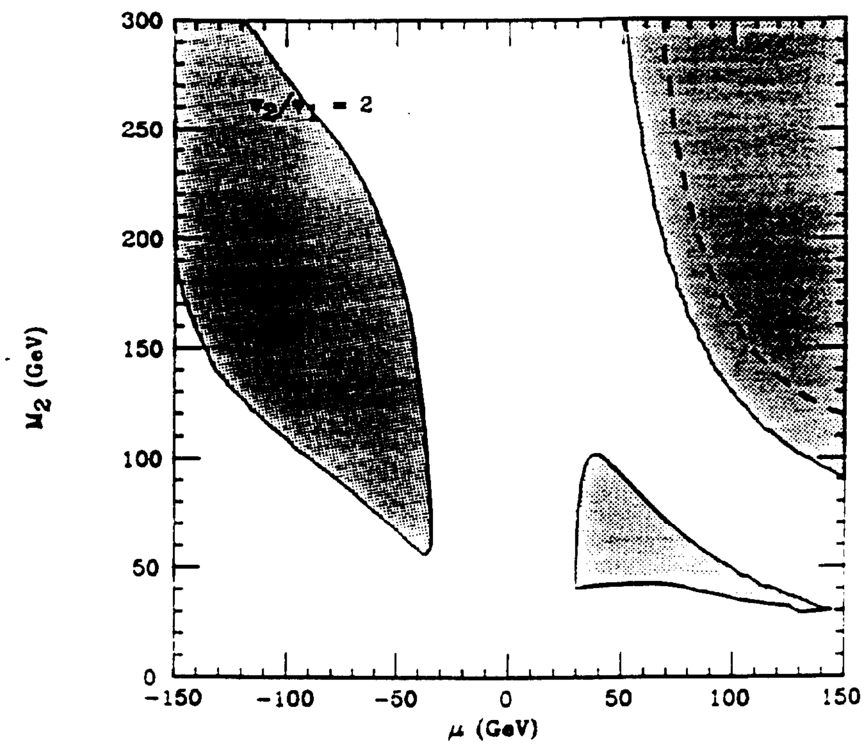

Fig. 2

The experimental signal again depends crucially on the cross section of the halo particles with nuclei. In the case of the neutralino, as previously discussed, the dominant contribution to the scattering is likely to come from Higgs exchange¶. If the Higgs boson is not too heavy, neutralinos are efficiently captured by the sun and the earth and their annihilation produce a significant flux of energetic neutrinos.

¶Because of its abundance of hydrogen, the sun is also able to trap particles with spin dependent interactions. However, the light Higgs boson exchange strongly enhances the capture rate.

The neutrinos can be identified through production of electrons or muons (τ's are often kinematically suppressed) inside the underground detectors or through a muon shower generated by the ν_μ's in their interaction with the rock outside the detector. As shown in ref. 13, these events have observable rates, if the Higgs boson is lighter than about 30 GeV.

I wish to stress that the presence of light Higgs bosons and supersymmetry at the Fermi scale are deeply connected. The description of light scalars free from the naturalness problem needs the introduction of supersymmetry and, in the context of the most satisfactory models, supersymmetry necessarily implies a light Higgs (usually lighter than the Z^0).

The observation[14)] that a cold dark matter particle can solve the solar neutrino problem has generated much theoretical interest. The solution relies on well–defined properties of the candidate particle, called the cosmion. The cosmion, orbiting inside the sun after being captured, transports heat away from the core, depleting the expected ^8B neutrino flux.

In order to efficiently transport energy and not disappear through evaporation or annihilation, the cosmion should have a mass in the range 4–10 GeV, an effective cross section in the sun of about $4 \cdot 10^{-36} cm^2$ (about two orders of magnitude larger than a typical weak cross section) and a strongly suppressed annihilation rate. Remarkably, the neutralino can actually satisfy these requirements[15)]. The large cross section can be provided by the exchange of a Higgs boson with mass of about 1–2 GeV, which is at the experimental limit, but not yet excluded. The annihilation via s–channel Higgs boson exchange, which is naively expected to be very important, turns out to vanish in the s–wave and, therefore, is strongly suppressed by the low neutralino velocity. In a suitable range of parameters, the neutralino annihilation rate is small in all channels and the cosmion solution is allowed.

Let me turn now to discuss the case in which the sneutrino ($\tilde{\nu}$) is the LSP[16-17]. In supergravity models, we find one sneutrino and its antiparticle for each generation. They are expected to be almost degenerate in mass, but, because of the charged current renormalization effects, the τ sneutrino is likely to be the lightest. The other two $\tilde{\nu}$'s will decay into the lightest one and a pair of neutrinos, if no other fermions are kinematically allowed.

In the early universe, the sneutrino–antisneutrino pairs annihilate into ordinary fermions via Z^0–exchange, into neutrinos via neutralino exchange, or into electron–positron pairs through exchange of charginos, the charged spin–1/2 supersymmetric particles. In the limit of massless final fermions, all annihilation channels are p–wave suppressed. This can easily be understood by noting that, since the sneutrinos have spin zero, one can repeat the same helicity argument used for neutralinos. However, sneutrino–sneutrino annihilation $\tilde{\nu}\tilde{\nu} \rightarrow \nu\nu$ is also possible, by exchange of a Majorana neutralino in the t–channel. It is easy to realize that the helicity flip Majorana mass allows the process to occur in s–wave. Furthermore, the effect of the neutralino Majorana mass m_χ yields an annihilation rate proportional to m_χ^{-2}, as opposed to the ordinary weak annihilation of a dark matter particle with mass m_{DM} which goes like $m_{DM}^2 m_{Z^0}^{-4}$. This makes the sneutrino annihilation very fast. If we insist that the sneutrino is the major constituent of the dark matter, the channel $\tilde{\nu}\tilde{\nu} \rightarrow \nu\nu$ has to be suppressed. This is possible if the neutralinos that contain a $\tilde{Z}$ component are heavier than about 1–10 TeV. Then the annihilation of cosmic sneutrinos occurs mainly through Z^0, and sneutrino dark matter is possible in the mass range $m_{\tilde{\nu}} \simeq$ 4–20 GeV. However, one might regard this large mass hierarchy between the neutralino and the sneutrino as rather unattractive. Another possibility for the suppression of $\tilde{\nu}\tilde{\nu} \to \nu\nu$ is an accidental cancellation between the contributions of the different intermediate neutralino states. This cancellation indeed occurs in the limit $M, \mu \to 0$[16]. This in turn implies that some neutralino states are very light and therefore, since the sneutrino is the LSP, it should be lighter then few GeV.

Unlikely the Majorana neutralinos, the sneutrinos can have a cosmic asymmetry which may help in providing a larger relic density. Of course, if the channel $\tilde{\nu}\tilde{\nu} \to \nu\nu$ is accessible, any initial sneutrino cosmic asymmetry becomes irrelevant[18].

Although the mechanisms for providing sneutrino dark matter seem a little contrived, one is always interested in the actual experimental limits. Since the $\tilde{\nu}$ has a coherent weak interaction with nuclei through Z^0–exchange, the Ge detector experiments can exclude a sneutrino heavier than 12 GeV as a main component of the galactic halo[8]. The same interaction can trap the $\tilde{\nu}$'s in the sun and the earth, if they are heavier than respectively about 3 and 10 GeV, the evaporation masses. The consequent $\tilde{\nu}\tilde{\nu} \to \nu\nu$ annihilation leads to a distinctive monochromatic neutrino signal, most likely made of ν_τ's. If the channel $\tilde{\nu}\tilde{\nu} \to \nu\nu$ is strongly suppressed, the $\tilde{\nu}$'s still provide energetic neutrinos coming from the decay of heavy quarks produced in the $\tilde{\nu}\bar{\tilde{\nu}} \to q\bar{q}$ annihilations. In this case, the neutrinos have a broad energy spectrum, similar to the one generated by the annihilation of neutralinos.

The last supersymmetric dark matter candidate I want to examine is the gravitino, the spin 3/2 partner of the graviton. Since the gravitino has only gravitational couplings, its annihilation in the early universe proceeds extremely slowly. If the gravitino is stable, then in order not to overclose the universe, it should be lighter than about 1 keV[19]. Therefore, it seems that this is the mass range in which gravitinos are candidates to be the dark matter. Although such an ultralight gravitino is difficult to understand in the context of the ordinary supergravity models, it can be predicted in the so-called "no-scale models"[20]. However, if the universe has undergone a period of inflation, the scenario for gravitinos is drastically changed. Gravitinos are washed out by inflation, but then regenerated if the reheating temperature T_R is larger than the mass of the supersymmetric particles[21]. In this case, the gravitinos are relevant for dark matter if $m_{\tilde{G}} T_R \lesssim 10^{14}\ GeV^2$, where $m_{\tilde{G}}$ is the gravitino mass. In order to allow the occurrence of the standard mechanism for baryongenesis, T_R must be larger than about 10^{12} GeV. Therefore, gravitinos with mass up to 100 GeV can be proper candidates for dark matter.

If the gravitino is the LSP, the next-to-lightest supersymmetric particle (NSP) is constrained to annihilate efficiently in the early universe. Actually, at a time $t_D \sim M_P^2 m_{NSP}^{-3} \sim (100\ GeV/m_{NSP})^3 \cdot 10^8$ sec (i.e., after nucleosynthesis) the relic NSPs decay into a gravitino and an ordinary particle. If the density of NSPs at the time t_D is sizable, the energetic decay products can in general interact with the nuclei and upset the successful predictions of the standard nucleosynthesis.

In collider experiments, since the NSP is so nearly stable, it has the usual "missing energy" signature and is indistinguishable from an ordinary LSP. Therefore, in this scenario, the particle which can be experimentally identified as the LSP, does not coincide with the supersymmetric dark matter candidate.

Due to the weakness of the gravitational force, the direct detection of gravitinos in the galactic halo looks hopeless. A similar situation is encountered in the case of "shadow matter". Many supergravity and superstring models predict the existence of "hidden" or "shadow" matter, which is necessary to break some extra symmetries of the theory at ultra high energies, and which couples only gravitationally to ordinary matter. Although the idea that the halo is made up of a shadow world is very stimulating and has interesting cosmological and astrophysical consequences[22], unfortunately at present has little experimental significance.

Finally, I want to mention that the gravitino can cause a cosmological difficulty, if it is not the LSP. An unstable gravitino decays no earlier than a time $\tau \sim M_P^2 m_{\tilde{G}}^{-3} \sim (100\ GeV/m_{\tilde{G}})^3 \cdot 10^8$ sec. This means that the nucleosynthesis predictions are upset by late entropy production, unless $m_{\tilde{G}} \gtrsim$ 10 TeV[23]. However, one attractive feature of the supergravity models is that the breaking of supergravity sets the scale for the electroweak symmetry breaking. Since the gravitino mass is the signal for supergravity breaking, one expects $m_{\tilde{G}} \simeq 0(m_W)$. Even if inflation is assumed, this contradiction can not be solved. Disassociation of light elements by the gravitino decay products constrains the reheating temperature T_R to be less than about 10^8 GeV[21], too low to allow standard baryongenesis.

A possible solution to this problem is found in scenarios where the gravitinos decay mainly into neutrinos and LSP's[24], thus circumventing the limits from entropy production, nucleus dissociation and microwave background distortion. The late gravitino decay can provide the right amount of LSP's in order to account for dark matter. Since the LSP's are now decoupled, they lead to $\Omega \simeq 1$, independently of their annihilation rate. For instance, this mechanism for dark matter production can explain a present relic abundance of sneutrinos which is difficult to achieve in the standard scenario, as seen above.

In conclusion, I have shown that supersymmetry offers interesting explanations for the existence and the nature of the dark matter. Notably, if the neutralino is the LSP, the dark matter seems an almost unavoidable prediction of supergravity theories. The present experimental situation looks very promising too. The development of cryogenic detectors[11)] will greatly increase the sensitivity in the search for the dark matter and, hopefully, we will be able to know what our universe is mainly made of.

References

[1] For reviews see Faber, S.M. and Gallagher, J.S., Ann. Rev. Astron. Astrophys. 17, 135 (1979); Trimble, V., Ann Rev. Astron. Astrophys. 25, 425 (1987); "Dark Matter in the Universe", Proc. of the Int. Astron. Un. Symp. No. 117, eds. J. Kormendy and G.R. Knapp (1987).

[2] Goldberg, H. and Hall, L.J., Phys. Lett. B174, 151 (1986).

[3] For reviews see Haber, H.E. and Kane, G.L., Phys. Reports 117, 75 (1985); Barbieri, R., Riv. Nuo. Cim., 11 (1988).

[4] Ellis, J., Hagelin, J.S., Nanopoulos, D.V., Olive, K. and Srednicki, M., Nucl. Phys. B238, 453 (1984).

[5] Griest, K., Phys. Rev. D38, 2357 (1988).

[6] Goldberg, H., Phys. Rev. Lett. 50, 1419 (1983).

[7] Barbieri, R., Frigeni, M. and Giudice, G.F., Pisa preprint IFUP-TH 8/88 (1988), to be published in Nucl. Phys. B.

[8] Ahlen, S.P. et al., Phys. Lett. 195B, 603 (1987); Caldwell, D.O., et al., Phys. Rev. Lett. 61, 510 (1988).

[9] Goodman, M.W. and Witten, E., Phys. Rev. D31, 3059 (1986).

[10] Shifman, M.A., Vainshtein, A.I. and Sakharov, V.I., Phys. Lett. 78B, 443 (1978).

[11] For a review on detection of dark matter, see Primack, J.R., Seckel, D. and Sadoulet, B., Santa Cruz preprint SCIPP 88/14 (1988), to be published in Ann. Rev. Nucl. Part. Sci., and references therein.

[12] Losecco, J.M., et al., Phys. Lett. 188B, 388 (1987); Kuznik, B., Orsay preprint LAL–87–21 (1987); Totsuka, Y., Tokyo preprint UT–ICEPP–87–02 (1987).

[13] Giudice, G.F. and Roulet, E., ISAS–Trieste preprint S.I.S.S.A. 103 EP (1988), to be published in Nucl. Phys. B.

[14] Spergel, D.N. and Press, W.M., Ap. J. 294, 663 (1985); Faulkner, J. and Gilliland, R.L., Ap. J. 299, 994 (1985).

[15] Giudice, G.F. and Roulet, Fermilab preprint FERMILAB–PUB–88/129–T (1988), to be published in Phys. Lett. B.

[16] Hagelin, J.S., Kane, G.L. and Raby, S., Nucl. Phys. B241, 638 (1984).

[17] Ibañez, L., Phys. Lett. 137B, 160 (1984).

[18] Griest, K. and Seckel, D., Nucl. Phys. B283, 681; E B297, 1034 (1988).

[19] Pagels, H. and Primack, J.R., Phys. Rev. Lett. 48, 223 (1982).

[20] For a review see Lahanas, A.B. and Nanopoulos, D.V., Phys. Reports 145, 1 (1987).

[21] Ellis, J., Kim, J.E. and Nanopoulos, D.V., Phys. Lett. 145B, 181 (1984).

[22] Kolb, E., Seckel, D. and Turner, M., Nature 314, 415 (1985).

[23] Weinberg, S. Phys. Rev. Lett. 48, 1303 (1982).

[24] Frieman, J. and Giudice, G.F., Fermilab preprint FERMILAB-PUB-89/18-T (1989).